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SOME ASPECTS OF AIRCRAFT DYNAMIC ~~LOADS DUE~~ TO FLOW SEPARATION

by

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(February 1988

Paper presented at the 65th Meeting of the Structures and Materials Panel of AGARD,
in Çeşme, Turkey, 4—9 October 1987.

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ABSTRACT

SOME ASPECTS OF AIRCRAFT DYNAMIC LOADS DUE TO FLOW SEPARATION

This paper discusses various topics associated with the study of Aircraft Dynamic Loads due to Flow Separation. Topics discussed include the need for consistent definitions of buffet and buffeting, the advantages of a consistent notation for all the papers, buffeting due to wings and other components, the alleviation of buffeting, the special difficulties of flight tests and the special advantages of buffeting measurements in cryogenic wind tunnels.

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RESUME

UNE APPROCHE AU PHENOMENE DES CHARGES DYNAMIQUES IMPOSEES AUX AERONEFS PAR LE DECOLLEMENT DES ECOULEMENTS D'AIR

La présente Communication traite un certain nombre de thèmes relatifs à l'étude des charges dynamiques imposées aux aéronefs par le décollement des écoulements d'air. Parmi les sujets abordés nous citerons: la nécessité de donner une définition uniforme du terme "tremblement", les avantages d'un système de numérotation standardisé pour les Communications, le tremblement dû aux voilures et à d'autres éléments structuraux, l'atténuation du tremblement aéroélastique, les difficultés inhérentes aux essais en vol et les avantages spécifiques procurés par l'emploi de souffleries cryogéniques.

CONTENTS

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SUMMARY

This Pilot Paper to be presented at the AGARD SMP meeting in Cesme, Turkey, in October 1987, suggests topics for an AGARD specialist meeting on "Aircraft dynamic loads due to flow separation", planned for 1989.

Topics discussed include the need for consistent definitions of buffet and buffeting, the advantages of a consistent notation for all the papers, buffeting due to wings and other components, the alleviation of buffeting, the special difficulties of flight tests and the special advantages of buffeting measurements in cryogenic wind tunnels.

Single degree of freedom flutter due to flow separation is not discussed, but should be considered at the meeting.

LIST OF SYMBOLS AND UNITS

		SI	British
C_B	rms wing root strain signal/kinetic pressure see equation (9)	V m^2/N	V ft^2/lbf
C'_B	buffeting coefficient see equation (10)		
C''_B	corrected buffeting coefficient see equation (11)		
C_L	lift coefficient		
C_{Lb}	lift coefficient at buffet onset		
c	chord	m	ft
$\bar{c}$	standard (geometric) mean chord	m	ft
c_t	wing tip chord	m	ft
c_0	centre-line chord	m	ft
f	frequency	Hz	Hz
f_1	wing fundamental bending frequency	Hz	Hz
Δf	analyser bandwidth	Hz	Hz
F(n)	contribution to power spectrum of $\bar{p}/q^2$ in a frequency parameter band Δn		
$\sqrt{nF(n)}$	level of pressure fluctuations see equation (1)		
$\sqrt{nG(n)}$	buffet excitation parameter see equation (7)		
G(n)	non-dimensional spectral density of aerodynamic excitation (as defined in Refs 9, 11, 27, 31)		
K	factor in equation (9)	V m^2/N	V ft^2/lbf
L	reference length for frequency parameter and Reynolds number (L = c, $\bar{c}$, ℓ or w)	m	ft
ℓ	bubble length	m	ft
M	Mach number		
m	generalised mass see equation (7)	kg	slug
n	frequency parameter, fL/U		
p	pressure	N/m^2	lbf/ft^2
$\bar{p}$	rms pressure fluctuations	N/m^2	lbf/ft^2
Δp	rms pressure fluctuation in frequency band Δf at frequency f	N/m^2	lbf/ft^2
q	kinetic pressure	N/m^2	lbf/ft^2
R	unit Reynolds number		
R_i	instantaneous resistance of strain gauge i	Ω	Ω
S	reference area of planform (exposed wing)	m^2	ft^2
t	thickness	m	ft
U	free-stream velocity	m/s	ft/s
V	voltage applied to Wheatstone bridge circuit	V	V
ΔV	output signal from Wheatstone bridge circuit	V	V
w	wind-tunnel width	m	ft
x	streamwise distance from bubble separation point	m	ft
x_s	chordwise location of shock wave	m	ft
x_0	axial distance of leading edge of c_0 from nose tip (see Fig 15)		
z	wing tip deflection	m	ft
$\ddot{z}$	rms wing tip acceleration see equation (7)	m/s^2	ft/s^2
α	incidence	degree	degree
α_f	foreplane effective incidence	degree	degree
α	angle of incidence	degree	degree
γ	ratio of aerodynamic damping to the critical		
ε	analyser band width ratio, $\Delta f/f$		
ζ	ratio of total damping to the critical see equation (7)		
η	spanwise distance from root as fraction of semi-span		

η_f	foreplane setting	degree	degree
Λ	sweep of quarter chord line or leading edge	degree	degree

1 INTRODUCTION

The AGARD Structures and Materials Panel (SMP) plans to arrange a specialists meeting on "Aircraft Dynamic Loads due to Flow Separation", probably in the Spring/Autumn of 1989. The AGARD-SMP thought that some guidance should be offered on the types of problem of interest. Hence two pilot papers were requested. The first pilot paper, by Prof H. Försching, addresses the analytic and numerical aspects of aircraft dynamic loading[1]. Ref 1 is complemented by the present paper, which addresses the experimental problems of both wind tunnel and flight tests.

Aircraft dynamic loads due to flow separation are often totally unknown, or ignored or underestimated during the design process. This uncertainty is unlikely to cause failure in primary structures (Fig 1a), which are designed generally by static strength requirements or by stiffness criteria necessary to avoid flutter. However the uncertainty is more likely to cause fatigue failures in secondary structures, such as flap brackets, ailerons, rudders or the rear fuselage (Fig 1b). Such failures can be costly to remedy once an aircraft is in service. One main objective of the specialist meeting in 1989 should be to reduce this uncertainty by carefully quantifying some of the dynamic loads appropriate to a wide range of configurations (Fig 2). The emphasis in this Paper is on dynamic loads due to buffet excitation (Fig 2a-g), but dynamic loads due to amplitude-limited single-degree of freedom flutter should also be considered at the meeting (Fig 2i).

In many previous investigations the dynamic loads have not been quantified because of the failure to adopt a consistent set of definitions and notation. An important aspect of AGARD's work is to urge the adoption of consistent definitions and notation for various problems. The author suggests that the notation widely used in Europe should be adopted formally by AGARD. Then in the selection of papers for the 1989 meeting, preference could be given to authors who conform to these definitions and adopt the notation. A common notation would greatly facilitate comparison of experimental results.

In addition to the questions of definitions and notation, other topics are considered in this Paper. The criteria for dynamic loading for transport and combat aircraft are radically different and are briefly reviewed. The importance of the generalised force coefficient (or buffet excitation parameter) to particular modes is stressed and detailed instructions are given for the derivation of the buffet excitation parameter from measurements in both wind tunnel and flight tests. As an illustration of the dynamic buffeting loads on wings, a careful re-evaluation of Ray's systematic buffeting measurements[2] is given, based on Ref 3. Then an important class of interference problems is considered: the effect of canard separations on wing and tailplane loads. The special difficulties inherent in flight tests are discussed briefly and a plea is made to the Computational Fluid Dynamics Community to predict two special types of buffet excitation.

It is hoped that this wide ranging discussion will stimulate interest in the subject and that all these topics will be addressed in much greater depth at the specialist meeting.

2 DEFINITIONS AND NOTATION RECOMMENDED TO AGARD

2.1 Definitions

Buffeting is defined already in Ref 4 as the structural response to the aerodynamic excitation provided by separated flows. Unfortunately the term buffet is also defined as a response in Ref 4. However, it was suggested by the present author in Ref 5 that buffet should be defined as the aerodynamic excitation provided by separated flows (Fig 3), such excitation being independent of any structural motion. The author suggests that AGARD should now formally adopt this definition. Some comments on buffet and buffeting may be helpful to readers who are not specialists in this area.

The buffet or aerodynamic excitation associated with separated flows is normally random in character and covers a wide frequency range[5]. However, for a few separated flows the buffet is periodic and exists at a single frequency. A well known and important example of this type of periodic excitation is that provided by the Karman vortex street behind a rigid circular cylinder at sub-critical Reynolds numbers[6]. A less well-known, but important type of periodic buffet excitation is provided by the shock oscillations on thick bi-convex aerofoils set at zero incidence at transonic speeds[7,8].

The buffeting, or structural response to buffet, can only occur at appropriate aircraft frequencies. These frequencies are those for rigid body modes (heave, pitch and roll may be excited) and structural modes. Important modes of primary structures are the first bending and first torsion of the wing, the tail unit and the fuselage. If any of these modes occur at the same frequency, their motion may become 'coupled' and particularly large responses may be expected, beyond the scope of this Paper. Little information is currently available about the modes excited in secondary structures, which may give fatigue failures.

For predictions of buffeting it is useful to regard the aircraft structure as a selective filter, which allows response to the appropriate part of the excitation spectrum[9]. Normally the magnitude of the buffeting response is restricted by the total damping coefficient appropriate to the mode under discussion. It is not generally recognised that for ordinary wind tunnel models (made of steel) tested in conventional wind tunnels the damping coefficient is predominately structural and typically is only about 1 to 2% critical[10]. In complete contrast, in flight the damping coefficient is often predominately aerodynamic, and may vary between, say 4 and 10% critical in attached flows[11,12]. This creates special problems in the extrapolation from wind tunnel to flight tests. These problems are discussed in section 5.4.

For completeness, it should be noted that when separated flows excite single degree of freedom flutter or buzz, the structure adopts a limit cycle motion, with an amplitude determined by the requirement that the total damping coefficient (averaged over a complete cycle) should be zero[13]. For such motion the mode generally remains the same as for attached flow (although there may be a small change in frequency). Discussion of these motions is beyond the scope of this Paper. However, these motions are important (cf the Paper by Moss and Pierce on the torsional buzz of a swept wing[14]) and should be included in the 1989 conference (see Fig 21).

2.2 Notation

2.2.1 Buffet

It is recommended that the buffet, or excitation, should be presented as a function of the free stream kinetic pressure, q_∞. Thus the total broad-band rms pressure fluctuation, $\bar{p}$, is expressed as the ratio $\bar{p}/q$.

The buffet excitation spectra should also be expressed in terms of q . The notation suggested by Owen[15] is recommended (Fig 4).

$$\bar{p}^2/q^2 = \int_{n=0}^{n=\infty} F(n)\,dn = \int_{\log n = -\infty}^{\log n = -\infty} nF(n)\,d(\log n) \,, \tag{1}$$

where

$\bar{p}^2$ = power of pressure fluctuations,

n = fL/U - frequency parameter,

$F(n)$ = contribution to $\bar{p}^2/q^2$ in a frequency parameter band Δn ,

L = reference length.

In buffet investigations the excitation spectra are frequently represented in the rms form, by plotting $\sqrt{nF(n)}$ against either frequency or log n. If the rms pressure fluctuations are measured with a spectrum analyser of constant bandwidth ratio, $\Delta f/f = \varepsilon$, and the pressure fluctuations within this bandwidth at a frequency parameter n are Δp then,

$$\sqrt{nF(n)} = \frac{\Delta p}{q\sqrt{\varepsilon}} \,. \tag{2}$$

Typical values of $\bar{p}/q$ can be associated with different types of flow (Fig 5a). Thus for an attached flow with a zero pressure gradient the surface pressure fluctuations are given by[16]

$$\bar{p}/q = 0.005 \text{ to } 0.006 \,. \tag{3}$$

For a boundary layer under an adverse pressure gradient the pressure fluctuations increase and move to lower frequencies[17]. Under the reattachment point of a two-dimensional bubble

$$\bar{p}/q \simeq 0.10 \,, \tag{4}$$

as shown by the correlations published in Ref 18. If a separation is coupled with some form of aerodynamic resonance, levels of $\bar{p}/q$ from 0.20 to 0.60 may be obtained. Three examples of such aerodynamic resonances may be cited.

(1) Periodic shock oscillations at transonic speeds already mentioned[7,8].

(2) Bi-stable separation position on a wing: here the reattachment point alternates between points R1 and R2 and very large pressure fluctuations are generated[19].

(3) Coincidence of Karman vortex shedding frequency[6]

$$f = S^*U/d \,, \tag{5}$$

with the acoustic resonance frequency of a duct

$$f = \frac{n}{2}\frac{a}{H} , \qquad (6)$$

as described in Refs 20, 7. This phenomenon occurs in coolers and heat exchangers.

as described in Refs 20, 7. This phenomenon occurs in coolers and heat exchangers.

Important values of $\sqrt{nF(n)}$ are shown in Fig 5a. For an attached turbulent boundary layer, the maximum value of $\sqrt{nF(n)}$ is about 0.002 to 0.003, depending on the Reynolds number. For the flow at a reattachment point[18] $\sqrt{nF(n)}$ has a maximum value of about 0.06 at a frequency parameter (based on the bubble length, ℓ) of $n = f\ell/U = 0.8$ (see discussion of Fig 28 in section 9).

Normally when separation is combined with some form of aerodynamic resonance the buffet excitation is very large, and a single, discrete frequency predominates. Here strictly, a spectrum function does not exist, and hence levels of $\sqrt{nF(n)}$ cannot be quoted. However, for the tests of Ref 20 where bi-stable flows and large rms pressure fluctuations were generated on a swept wing by a range of leading-edge notches (eg see Fig 5b for $\alpha = 17°$), the buffet excitation did cover a somewhat wider frequency range, so that the excitation spectrum, $\sqrt{nF(n)}$, could be defined (Fig 5c).

2.2.2 Buffeting

It is recommended that the buffeting, or response, should be presented also as a function of the free stream kinetic pressure, q . Usually there is little value in the total rms value of the response, because many modes are involved. Instead, it is more convenient to express the rms response, $\ddot{z}$, in particular modes in terms of the buffet excitation parameter, given by[9,11,12]

$$\sqrt{nG(n)} = \frac{2}{\sqrt{\pi}} \cdot \frac{m\ \ddot{z}}{q\ S} \zeta^{\frac{1}{2}} , \qquad (7)$$

where m = generalised mass in mode with respect to motion at tip,

$\ddot{z}$ = rms tip acceleration in mode,

q = kinetic pressure,

S = reference area,

ζ = total damping - as ratio to critical damping.

The parameter $\sqrt{nG(n)}$ is called the buffet excitation parameter because it represents the generalised force acting on the wing in that mode, although it is derived directly from the response (buffeting) measurements. The author suggests that AGARD should adopt this definition.

For a wide range of wings levels of $\sqrt{nG(n)}$ corresponding with light, moderate and heavy buffeting in the first bending mode have been identified[11,12] and confirmed by subsequent wind tunnel and flight tests. These buffeting limits are (Fig 6a)

Buffeting	$\sqrt{nG(n)}$
Light	0.00075
Moderate	0.00150
Heavy	0.00300

(Fig 6a includes sketches showing the corresponding areas of attached and separated flows on a typical swept wing at low speeds.)

When bi-stable flow separations occur, levels of $\sqrt{nG(n)}$ as high as 0.017 have been measured[20] (Fig 6b corresponds with the extremely high buffet excitation presented in Fig 5b&c). Use of configurations having such high levels of the buffet excitation parameter in primary structural modes would be likely to have serious consequences for the modes of the secondary structure (cf Fig 1). For these modes (even if the buffet excitation parameter is much the same despite changes in mode shape and frequency parameter) the total damping is likely to be smaller - being predominately structural and thus only about 1 to 2% of critical. Hence response amplitudes are likely to be larger.

For the common type of random buffet excitation it has been found that the buffet excitation parameter in a particular mode only varies slowly with frequency parameter, n . In addition there is often only a small variation from bending mode to bending mode. Two radically different illustrations of this important observation are offered in Fig 7. Fig 7a&b show that the buffet excitation parameter for a 65° delta wing[11] is much the same for the first bending mode as for the fourth bending mode, despite large changes in the mode shape and an increase in frequency parameter by a factor of 5, at Mach numbers of 0.35 and 0.70. Fig 7c shows that the buffet excitation parameter for a fin immersed in the wake from a wing/fuselage[21] is much the same for the first bending mode as the second bending mode, again despite large changes in mode shape and on increase in frequency parameter by a factor of 3. Fig 7 suggests that useful buffeting predictions can be made from ordinary wind tunnel models, even if mode shapes and frequency parameters are not well represented. In particular, three important dynamic load problems (Fig 2a-c) can be addressed by measurements of the buffet excitation parameter for bending modes.

The expression for torsional modes (corresponding with equation (7) for bending modes) is

$$\sqrt{nT(n)} = \frac{2}{\sqrt{\pi}} \left[\frac{I\,\ddot{\theta}}{qSc}\right] \xi^{\frac{1}{2}} , \tag{8}$$

where $\ddot{\theta}$ = rms angular response in the torsional mode

and I = generalised inertia in mode.

Unfortunately no comparable buffeting measurements for torsional modes are yet available. Hopefully some buffeting measurements for torsional modes will be presented at the meeting. The buffeting of fins of some combat aircraft at high angles of incidence (Fig 2c) is sometimes in the torsional mode, but wing buffeting in torsional modes is unusual.

3 DIFFERENT CRITERIA FOR TRANSPORT AND COMBAT AIRCRAFT

With regard to aircraft performance the requirements of transport and combat aircraft are different (Fig 8). Transport aircraft are designed to cruise well below the buffet boundary. A severe gust (which occurs infrequently) may take a transport aircraft above the buffet boundary for a short period. This rare event must not create any structural or control problems and is generally more serious for the steady loads than for the fatigue loads. In contrast, combat aircraft cruise below the buffet boundary but will manoeuvre frequently well above this boundary. Hence for combat aircraft the buffeting loads may be significant with respect to the fatigue life of the structure. The semi-empirical method used to determine these buffeting contours (light, moderate and heavy) is described at the end of section 5.4.

4 DERIVATION OF THE BUFFET EXCITATION PARAMETER

There are two methods of deriving the buffet excitation parameter and the buffeting response for an aircraft or a model (Fig 9).

The first method is the measurement of root strain or accelerometer signals (Fig 9a). This method is described in detail here and utilizes the relative insensitivity of the buffet excitation parameter to variations in mode shape and frequency parameter (eg Fig 7). The aircraft or model acts as an analogue computer, integrating the buffet excitation in space and time and combining this with any modes being excited. The advantage of the method is its simplicity and reliability. Its disadvantage is that is only appropriate for primary structural modes and is inappropriate for secondary structures or rigid body modes. Secondary structures are quite difficult to represent, even on a large aeroelastic model.

The second method is the measurement of the buffet (excitation) a large number of points on all surfaces of a nominally rigid model (Fig 9b). The buffet can then be integrated in space and time, together with the mode of interest, to give the buffet excitation parameter in this mode. The advantage of this method is that in principle dynamic loads may be predicted for any mode within the frequency bandwidth of the measurements. Its disadvantage is that it requires a large number of closely spaced, expensive pressure transducers together with a large computer. In addition, if an attempt is made to extrapolate from model to full scale, an assumption must be made about the level of aerodynamic damping because aerodynamic damping cannot be derived from pressure measurements on the model once the flow has separated.

The predictions from both methods are subject to the limitations inherent in wind tunnel tests with separated flows on the model. Even with fixed transition, scale effects may be significant. In addition tests in conventional wind tunnels inevitably involve uncertainties due to static aeroelastic distortion. Effects of static aeroelastic distortion occur at full scale and can be reproduced on appropriately scaled models. A recent Paper[22] quotes a static deflection of 75 mm and twist of -3.2° at the tip of a wing of semi-span 2.9 m. The design has a high aspect ratio supercritical wing suitable for a transport aircraft. In contrast, effects of static aeroelastic distortion were considered relatively small in both flight and wind tunnel tests on the F-111 TACT aircraft configuration[23]. In a cryogenic tunnel the problem of static aeroelastic distortion is less serious, because Reynolds number may be increased at constant Mach number by lowering the total temperature, keeping the total pressure and kinetic pressure constant[24]. However in a cryogenic tunnel transition fixing becomes more difficult. The author hopes that a sufficient number of buffeting measurements from cryogenic tunnels will be submitted to the specialist meeting to allow a special session on this important topic, which was not discussed at the AGARD meeting on Unsteady Aerodynamics in 1985. In an attempt to encourage this, the author has reproduced in Appendix B an analysis of the first set of buffeting measurements in a cryogenic wind tunnel, due to Boyden[25].

5 WING BUFFETING

The measurement of unsteady wing-root strain or wing-tip acceleration is recommended as the standard method for the prediction of wing buffeting from wind tunnel tests.

The notes that follow outline the preparation of the model, the test procedure, the method of analysis and the possible extrapolation of the wind-tunnel measurements to flight. Similar techniques may be applied to measure the buffeting on other aerodynamic surfaces, such as canards, tailplanes and fins (Fig 2a-c).

5.1 Preparation of the model

Buffeting measurements may be made on ordinary wind tunnel models (made of steel or aluminium alloy) or on flutter models. (The advantage of using aluminium alloy or flutter models is that there may be significant aerodynamic damping in the total damping coefficient.)

Ideally a complete model should be selected for buffeting tests, so that both symmetric and anti-symmetric responses can be measured. If a half model is used, only symmetric responses can be measured. Four strain gauges should be applied on each wing and wired in two Wheatstone bridge circuits (Fig 10a) to measure the sum and difference of the bending moments. The first bridge signal giving the sum of the bending moments gives the symmetric response (Fig 10b). The second bridge signal giving the difference of the bending moments gives the anti-symmetric response (Fig 10c). A strong objection should be voiced against the common practice of providing four gauges on <u>one</u> wing of a complete model. This is not recommended because the signals from both the symmetric modes and anti-symmetric modes are additive (Fig 10d).

Buffeting is measured as output from the strain gauge bridges in volts. The buffet excitation parameter in any mode is given by equation (7).

In a wind-off ground resonance test prior to the wind-on tests two important modes should be identified:

(1) The rigid body roll mode (which gives a response signal predominately anti-symmetric) and

(2) the first wing-bending mode (which gives a response signal predominately symmetric).

For both of these modes a relationship must be derived between the rms wing tip acceleration, $\ddot{z}$, in the mode and the corresponding rms signal, dV. For both modes the generalised mass, m, must be determined either by calculation or by noting the change of frequency produced by the addition of small masses. In addition it is helpful to determine the wind-off structural damping in both modes and to establish whether these coefficients have any significant variation with the response amplitude. Variations in structural damping due to response amplitude or wing lift are undesirable because it will then be difficult to extract the contribution of the aerodynamic damping from the total damping measured with the wind on (see section 5.3).

5.2 Wind tunnel test procedure

Ideally the response signals will be measured in a pressurised conventional wind tunnel at constant Mach number (M) at two kinetic pressures (q) and two Reynolds numbers (R). The tests should be made with fixed transition, with the roughness height sized for the lower Reynolds number; the tests at the higher Reynolds number will be 'over fixed'. The tests should cover the range of aerodynamic parameters likely to influence wing buffeting, say for a combat aircraft

angle of incidence	0 to 30° (60°?),
foreplane setting	±10°,
spoiler settings	10°, 20°, 40°,
flap settings	20°, 40°.

5.3 Analysis of measurements

The rms responses in both modes are plotted as functions of the angle of incidence at each kinetic pressure. The point at which the signal level increases above the level due to ambient tunnel unsteadiness marks the point of buffet onset (Fig 10e). Generally buffet onset will occur somewhat earlier in the higher frequency, first wing bending mode than for the lower frequency, rigid body modes. This is because the initial, small scale separations, create high frequency buffet excitation rather than low frequency excitation. While making the measurements of $\ddot{z}$, z and ζ, it is essential to use a sufficiently wide bandwidth (ε) for the measurements, while excluding other modes. For a wind-tunnel model ζ is typically 1 to 3 per cent of critical damping, so that $\varepsilon = 0.1$ is adequate (ie 10 per cent bandwidth). For an aircraft, ζ is typically 5 to 10 per cent of critical damping, so that $\varepsilon = 0.2$ is adequate (ie 20 per cent bandwidth).

A few selected signals should be recorded on magnetic tape, so that accurate values of the total wind-on damping ratio, ζ, can be determined by standard techniques (such as the measurement of the half-power point[10] or the 'random-dec' method[26] used in Ref 27. Thus knowing m , $\ddot{z}$, q , S_n and ζ the buffet excitation parameter may be calculated according to equation (7).

Experience on a wide range of configurations[12] covering combat aircraft and slender wings (both in wind-tunnel and flight tests) suggested the criteria for buffeting in the first wing bending mode, based on reference length $L = \bar{c}$, given already in Fig 6a.

These buffeting criteria are absolute coefficients, but their derivation requires careful measurements of m , $\ddot{z}$ and ζ . This may not be possible, in which case for comparative wind-tunnel tests (say, when differing wing designs are being evaluated) the level of flow unsteadiness at the frequency of interest may provide a scale of the severity of buffeting, to be related with the measured model response. This method is based on equation (7) and a number of carefully specified assumptions described in Ref 28.

The basic hypothesis is that the low-level response of the model wing to the unsteadiness in the air stream before the onset of significant flow separations on the model can be linearly related to the small-scale tunnel unsteadiness and that the tunnel unsteadiness does not interfere with the development of the flow separations.

At any angle of incidence above buffet onset the wing responds to both the base-level tunnel unsteadiness and the buffet pressure fluctuations. If it is assumed that the same linear relationship between the wing response and the tunnel unsteadiness applies as between the wing response and the buffet pressures, model response is then a direct measure of the buffet pressures and may be calibrated from its response to the known tunnel unsteadiness. If this hypothesis holds, then curves of unsteady wing-root strain (model response) against angle of incidence can be transformed into curves showing the variation of equivalent excitation or buffeting coefficients on the model. The corresponding excitation below buffet onset is the tunnel unsteadiness function, $\sqrt{nF(n)}$, at the wing fundamental bending frequency, f_1 .

The tunnel unsteadiness $\sqrt{nF(n)}$ is defined according to Ref 15 and equations (1) and (2).

Fig 11a shows a typical curve of unsteady wing-root strain at the wing fundamental frequency, f_1 , plotted against angle of incidence (taken from Ref 29). The flow is assumed to be insensitive to changes in Reynolds number, and the total damping of the wing fundamental mode is regarded as constant. Then

$$\text{wing-root strain signal}/q = C_B(M, \alpha) , \tag{9}$$

where $C_B(M, \alpha)$ is a dimensional function which is independent of q when M and α are given. Before the onset of flow separations on the model, most of the curves in Ref 26 and results from other tests[2] show that C_B is also independent of α . This is the portion of the model response caused by the tunnel unsteadiness, $\sqrt{nF(n)}$, at the appropriate Mach number and the same frequency, f_1 , and we may write

$$C_B(M,0) = K\sqrt{nF(n)} ,$$

and then

$$C'_B(M,0) = \frac{1}{K} C_B(M,0) = \sqrt{nF(n)} , \tag{10}$$

where $C'_B(M,0)$ is dimensionless and 1/K is a scaling factor.

This scaling factor is different for every model and will depend on the mass and stiffness distribution of the model, the sensitivity of the strain gauges and also the total damping in the fundamental mode. It is not necessary to assume the same scaling factor $1/K$ for all Mach numbers, but if so, the dimensionless model-response $C'_B(M,0)$ can be directly compared to the tunnel unsteadiness $\sqrt{nF(n)}$. There may be some variation of $1/K$ with M in the wind tunnel, but it is often convenient to use a fixed value to be applied to C_B for all Mach numbers. If the same scaling factor $1/K$ is also applied to the coefficients $C_B(M, \alpha)$ above buffet onset, curves of C'_B against α are obtained for a fixed M , and a typical example is shown in Fig 11b. The level C'_B at $\alpha = 0$ represents the tunnel unsteadiness and the model response to that unsteadiness. The subsequent increase in C'_B as the angle of incidence increases gives a measure of the integrated pressure fluctuations arising from the wing buffet and of the model response to this excitation. Having used the tunnel unsteadiness, $\sqrt{nF(n)}$, to establish a datum buffeting scale, this signal must now be subtracted to estimate the buffeting level in the absence of tunnel unsteadiness. Thus a corrected buffeting coefficient can now be calculated by the formula

$$C''_B(M, \alpha) = \sqrt{C'_B(M, \alpha)^2 - C'_B(M, 0)^2} . \tag{11}$$

The angle of incidence at which $C''_B(M, \alpha)$ first differs from zero is buffet onset. Buffeting coefficients are then readily obtained as functions of Mach number and angle of incidence or lift coefficient. Comparisons of the contours of the corrected buffeting coefficient, C''_B, of nine aircraft models with full-scale flight-test data[28] suggest the following semi-empirical criteria for the severity of wing buffeting.

Buffeting criteria of Ref 28

Level of C''_B	Buffeting criterion
0.004	Light
0.008	Moderate
0.016	Heavy

5.4 Extrapolation from wind-tunnel measurements to full scale

If there is negligible scale effect between the buffeting measurements at the different test Reynolds numbers and no reason to expect any more between these test Reynolds numbers and full scale, the wind-tunnel measurements of $\sqrt{nG(n)}$ based on $L = \bar{c}$ may be plotted conveniently as contours in the (M, α) or (M, C_L) domain.

However, estimation of the damping ratio ζ at full scale requires some care. The difficulty is not the choice of the structural damping coefficient (typically about 0.5 per cent critical) but rather the level of the aerodynamic damping coefficient appropriate to separated flows (typically about 5 per cent critical). For approximate estimates of buffeting it is reasonable to assume that after buffet onset the aerodynamic damping in the first wing bending mode remains at the attached flow level which should be known from flutter calculations. However, most wind-tunnel[30] and flight measurements show that due to flow separation the aerodynamic damping coefficient in this mode increases significantly. This increase in damping, ζ, reduces the level of response, $\ddot{z}$, for a given value of $\sqrt{nG(n)}$ and should be considered for accurate estimates. It should be noted that in the torsional mode the aerodynamic damping often decreases significantly after buffet onset and this can lead to single degree of freedom flutter or buzz (Refs 14 and 30).

If the wind-tunnel model has significant aerodynamic damping, then it is possible to extrapolate measured variations in model aerodynamic damping due to flow separation to full scale, eg using the relations given by Jones[9,31].

Fig 12 (from Ref 12) illustrates typical results obtained by applying equation (7) to the dynamic measurements described above and shows the variation of the buffet excitation parameter, $\sqrt{nG(n)}$, with incidence for several configurations. Figs 13 and 14 (from Ref 31) show two examples of comparisons of predicted and flight-measured results for $\ddot{z}$ against incidence and normal force. The predicted values for $\ddot{z}$ are calculated for the first wing-bending mode using equation (7) with full-scale values for m, q, S and ζ and with the level of $\sqrt{nG(n)}$ taken as that calculated from the wind-tunnel tests.

6 BUFFETING TESTS ON A SYSTEMATIC SERIES OF WINGS

Some systematic buffeting measurements on eleven swept wing models of high aspect ratio made by Ray and Taylor[2] illustrate[3] some interesting general effects of wing design variations on both the onset and the severity of buffeting according to the semi-empirical criteria of section 5.3. In addition these measurements provide useful bench marks for prediction methods for the onset of buffeting, at least for transport aircraft configurations.

6.1 Experimental details abstrated from Ref 2

An axially symmetric, steel fuselage was tested in conjunction with eleven steel wings mounted in a high position on the body. This series of models was based on the simply defined configuration in Fig 15 (Wing 2). The other ten models differ from Wing 2 in that one of the following five parameters is varied: quarter-chord sweepback, camber, thickness/chord ratio, position of maximum thickness, aspect ratio.

Four strain gauges were located on each of the starboard wings as in Fig 10d, so that the Wheatstone bridge responded to both symmetric and anti-symmetric wing distortion modes and the rigid body heave and roll modes. The rigid body motions due to normal force and rolling moment fluctuations may have been significant, because the models were supported on a flexible six-component balance. Ray and Taylor noted that buffet onset was sometimes masked by the level of flow unsteadiness in the tunnel. Nevertheless, it is likely that if the response had been measured in each of the modes, buffet onset would have been defined more precisely for these difficult conditions.

The measurements were made at fairly low Reynolds numbers (only about $R = 1.5 \times 10^6$ at $M = 0.6$), and transition was fixed at about 8 per cent chord from the leading edge on both surfaces of the wing, and also on the fuselage. With the aerofoil sections used for the tests scale effects should have been comparatively small with fixed transition.

6.2 Typical variation of buffet onset with Mach number

Fig 16 shows curves of the lift coefficient for buffet onset, C_{Lb}, against Mach number, M, which are typical of the wings in Fig 15. Generally (Fig 16a) for subsonic speeds C_{Lb} falls slowly as M increases up to $M = 0.6$. Usually (for sections of moderate thickness/chord ratio) in this speed range the separation is initiated at the leading edge (typically at about $\eta = 0.8$) and occurs at lower values of C_{Lb} as M increases, because stronger compressibility effects always increase the adverse pressure gradients in the leading-edge region. In general, configuration changes that increase the leading-edge radius will reduce the adverse pressure gradients and raise C_{Lb}. For low transonic speeds (Fig 16a) it is typical that the lift coefficient for buffet onset falls more rapidly before it starts to increase when M is above 0.8. In this speed range separation is initiated in a complex three-dimensional shock system at about midchord and $\eta = 0.8$. At first the initial separation moves upstream as Mach number increases and in consequence C_{Lb} decreases, but with further increases in M this trend is reversed. In general, configuration changes which increase three-dimensional effects and weaken the shocks will raise buffet boundaries.

In model tests at fairly low Reynolds numbers the boundary between leading-edge separation and shock induced separations sometimes induces a bi-stable flow accompanied by violent buffeting, (Fig 16b). There is some evidence in Ref 2 that bi-stable flows did occur.

For higher speeds the shock induced separation approaches the trailing edge. Then the area exposed to buffet excitation becomes small, the excitation moves to higher frequencies and perturbations travel slowly upstream from the trailing edge to the shock. The overall effect of these changes is to reduce the gradient of the severity of buffeting after buffet onset. In particular, buffeting will generally be light on all swept wings in supersonic flight except perhaps for high angles of incidence (say $\alpha > 15°$).

6.3 Results of systematic tests

Effect of sweep

Fig 17a shows the variation of the C_{Lb} with M for sweep angles of 25°, 35° and 45° and constant thickness/chord ratio. For subsonic speeds, where there is leading-edge separation, increasing sweep lowers the buffet boundary. In contrast, for transonic speeds, increasing sweep raises the buffet boundary, primarily because increasing sweep increases the three-dimensional character of the shock system and thus weakens it.

Some general remarks about the severity of buffeting follow from the variation with Mach number of the lift coefficient at which buffeting becomes moderate (see section 5.3). The contours for moderate buffeting are virtually the same for $\Lambda = 25°$ and 35° (Fig 17b). However, for $\Lambda = 45°$ the moderate buffeting contour is appreciably higher at Mach numbers above 0.4 and reflects the development of a more highly three-dimensional bubble.

Effect of camber

For subsonic and low transonic speeds positive camber raises the buffet boundary significantly (Fig 18a). This is because an increase in camber reduces the adverse pressure gradients in the leading-edge region and hence delays the onset of leading-edge separation. Above $M = 0.85$ the development of the three-dimensional flow is sensitive to the planform and section selected, and no general trend can be identified.

It is found that at both subsonic and transonic speeds, positive camber also increases the lift coefficient for moderate buffeting. This is the largest benefit achieved by the design variations tested (Fig 18b).

Effect of thickness/chord ratio

For subsonic speeds, increases in thickness/chord ratio raise the buffet boundary (Fig 19a). This is because as the aerofoil is scaled up in thickness the leading-edge radius increases, and thus reduces the adverse pressure gradients over the forward part of the wing. Thus leading-edge separation is delayed. In contrast, for transonic speeds increases in t/c generally lower the buffet boundary, because the shocks are strengthened and separation occurs earlier. Thus the thinnest section is greatly preferred above $M = 0.85$.

For the moderate buffeting contours the beneficial effect of increasing t/c at subsonic speeds (Fig 19b) is only slightly less than that for C_{Lb}. However, the severity of buffeting is found to be higher with the thicker sections at transonic speeds above $M = 0.85$, which is consistent with experience on aerofoils.

Effect of position of maximum thickness

For a given thickness/chord ratio, a significant effect of moving the maximum thickness aft is to decrease the leading-edge radius. Hence for subsonic speeds aft movement of the position of maximum thickness lowers the buffet boundary slightly (Fig 20a). For transonic speeds above M = 0.8 the trend is reversed. Possibly the predominant effect of the aft movement of maximum thickness is a general downstream movement of the sonic line. This would limit the extent of local supersonic flow, weaken the shock systems and raise C_{Lb} , but there is no corresponding trend in the moderate buffeting contours (Fig 20b).

Effect of aspect ratio

For subsonic speeds the present measurements show that the buffet onset boundary is raised slightly as aspect ratio and therefore lift-curve slope increases. In contrast, for transonic speeds C_{Lb} is lowered as aspect ratio increases (Fig 21a). This is because as aspect ratio increases the shock system tends towards the limit of that of an infinite swept-wing, which is 'quasi two-dimensional' and stronger so as to lower the buffet boundary. The moderate buffeting contour (Fig 21b) appears to show the benefit of increased lift-curve slope at subsonic and transonic speeds alike.

7 BUFFETING DUE TO OTHER COMPONENTS

An important problem which should be noted is the prediction of buffeting caused by flow interference. A classic example of this type of interference is the response of a tailplane immersed in the separated wake from a wing (Fig 2a). An early investigation of this problem introduced the term 'buffeting' into aeronautical literature[32]. There is evidence to suggest that the buffeting excitation parameter on a tailplane due to the wing wake may be up to several times the level of the heavy buffet excitation parameter due to flow separation on the tailplane buffeting. Exceptionally high values of $\sqrt{nG(n)}$ up to 0.012 are suggested, beyond the levels considered in Fig 6. Ideally, aircraft designs would ensure that the tailplane never became immersed in the wing wake. If this cannot be avoided, it should only be allowed to occur at low kinetic pressures after take-off and during the landing approach, and not when manoeuvring with high load factors at transonic speeds.

Another example of the problem is the buffeting of a wing due to the wake of a foreplane (Fig 2b). The crucial concept is that flow separation on the foreplane, and hence foreplane buffeting, is determined by the foreplane effective incidence, α_f . This is not simply the sum of the aircraft incidence and the foreplane setting (η_f) but involves the upwash due to the body and the wing. The wing buffeting measurements must be considered in the (α, η_f) domain, paying due attention to the corresponding values of α_f . At high incidence the vortex generated by the foreplane can have a beneficial effect in limiting the spread of the wing upper-surface separation and the growth of large-scale low-frequency excitation. As a consequence the growth of wing buffeting above α_{wb} is reduced significantly in the first bending mode.

This is illustrated by some buffeting measurements on a flutter model of an aircraft configuration with a typical foreplane/swept wing[33]. Fig 22a shows the measured buffeting characteristics of the foreplane in the α,η_f domain. The lines drawn for $\alpha_f = \pm 10°$ define the domain within which the foreplane flow is attached, and there is no canard buffeting. The lines $\alpha_f = +11.2°$, 16° and 26° correspond with light, moderate and heavy buffeting on the foreplane, according to equation (7). The dotted line indicates a typical canard schedule which might be required to trim an aircraft.

Fig 22b shows the corresponding characteristic for the wing buffeting in the first bending mode, also presented in the α , η_f domain. Three important features should be noted.

(1) Foreplane off measurements may be represented along the line $\alpha_f = 0°$.

(2) There is a large shaded area where there is no forced response on the wing due to the excitation from separations on the foreplane upper surface ($\alpha_f > 10°$).

(3) For high angles of wing incidence ($\alpha > 20°$) and separated flow on the foreplane there is strong favourable interference between the foreplane and wing flows, which reduces the wing buffeting. This favourable interference occurs along the canard schedule and is typical of the reductions in wing dynamic loading which may be obtained by a judicious choice of configuration.

Fig 22c shows the corresponding characteristic for wing buffeting in the second bending mode. Two important features should be noticed.

(1) The shaded area with no forced response due to foreplane excitation is appreciably smaller than for the first wing bending mode.

(2) The shape of the contours is appreciably different from those of Fig 22b. (These differences can be explained, but are beyond the scope of this Paper.)

Comparable problems may occur on fins, due to the excitation provided by foreplanes, fuselages or wings (see Fig 2c and Ref 34) or even by separations on rear fuselages (Fig 2d).

When flaps are fully deflected, the local flow over the upper surface is usually partially separated (Fig 2e). Although no measurements of buffet excitation are available, the frequent reports of flap failures on transport aircraft suggest that tests should be made to establish some design criteria. These criteria would recognise the high level of local buffet excitation and the importance of limiting the buffeting response to acceptable levels. Similar problems may also arise for spoilers and airbrakes (Fig 2f).

Buffeting due to flow interference occurs also on closely mounted stores at transonic speeds, (Fig 2g) and within cavities (Fig 2h).

In general, any bluff excrescence on an airframe, for example, scoop intakes, fairings, antennae and drains, can lead to significant areas of separated flow and hence buffeting. A example of a buffet-related problem arising from transonic flow around a cockpit canopy is discussed in section 8.2.

Unfortunately, very little exists in terms of design criteria for many of the problems mentioned above, but some guidance may still be obtained from the empirical data discussed in section 9.1 concerning bubble-type separations. Hopefully the specialist meeting will address all these problems.

8 ALLEVIATION OF BUFFETING

8.1 Reduction or elimination of flow separations

The most effective method of alleviating buffeting is to eliminate or at least reduce flow separations. Typical examples are given in Figs 23 and 24.

Fig 23, taken from Ref 35, shows the effect of deflecting a slat at the leading edge of a constant chord wing with 35° sweepback. At $M = 0.65$ the early stall of the basic wing was improved by reducing the high leading-edge suctions, and the slat allowed a much higher maximum lift to be produced. The increase in incidence achieved before the divergence of pressure recovery at the trailing edge emphasises the control over the onset of flow separation. This correlated well with a corresponding margin of incidence prior to the rise in buffeting response. Fig 24a shows comparable improvements in the incidence for buffet onset obtained over a wide range of Mach number by leading-edge slats on a tapered and more highly swept wing of lower aspect ratio suitable for a combat aircraft.

In a similar manner the deployment of a leading-edge droop can benefit separation onset conditions, but this might not provide the same modulation of the subsequent growth rate of buffeting as with a slat. However, slats are not easily engineered in thin wing sections. Advanced designs of combat aircraft wings might rely on a sophisticated variable camber leading-edge/trailing-edge flap system, which could be scheduled to optimise improvements in buffet boundaries throughout the required Mach number range.

In contrast Fig 24b shows other means of improving buffet onset for a transport wing of high aspect ratio. Streamlined area-rule bodies, fitted to the wing trailing-edge region, reduced the adverse pressure gradients and the spanwise flow tendency. The benefits were further enhanced by the addition of boundary-layer fences.

Recent research[36] suggests that short, low fences can be effective in controlling leading-edge flow separation at low speeds. However, it would be unwise to select a fence configuration which generates bi-stable flows, because these alternate between two levels of normal force coefficient and levels of buffeting.

Leading-edge blowing and blown flaps are also occasionally used as a means of reducing or delaying the onset of flow separation.

8.2 Stabilisation of separations

There are many flows for which separation cannot be prevented. However, many of these separations can be stabilised by judicious manipulation of the boundary conditions. The stabilised separations have much lower levels of buffet and generally have lower drags. Modifications of this type are often effective over a wide speed range and include vortex generators, leading-edge notches, base-bleed, and streamwise strakes within the separation. These strakes reduce the scale of the excitation, forcing it to higher frequencies. Both base bleed and strakes were applied to eliminate the buffeting on the Hercules tanker aircraft[37].

Wing leading-edge strakes have a powerful effect on wing buffeting. The highly swept leading edge of the strake develops a strong vortex at moderate angles of incidence, which may sometimes lower the buffet onset boundary, but greatly reduces the severity of buffeting at higher lift coefficients (see Fig 25 and Ref 38) in a manner similar to that of foreplane/wing interferences, see section 7.

In the context of flow over or around bluff fairings at transonic speeds, buffet breathers[39] are effective method of reducing large amplitude, low/medium frequency shock oscillation and hence reducing buffet. Buffet breathers are capable of refinement and are thought to have a wide range of applications.

Fig 26a illustrates the principle of a buffet breather installed in a bluff fairing. Suppose aerodynamic excitation is being provided at opposite points A and B by time-dependent pressure variations with a significant phase difference across the fairing, but with the same mean pressure over a long period. If points A and B are then connected by a short 'breather' tube (which need not be straight), the time-mean pressure may not be altered, but the time-dependent pressures will be attenuated due to the variable flow through the breather produced by the phase difference. The breather flow will be large when these time-dependent pressures are 180° out of phase. With a large breather flow the local buffet excitation will be reduced. The breather should operate over a range of frequencies from quasi-static up to some upper limit set by the acoustic response characteristics of the breather. For a given excitation frequency the limiting length and diameter of the breather can be determined by the method of Ref 40. The effect of installing buffet breather tubes on the rms pressure fluctuations around a bluff fairing is illustrated in Fig 26b.

One example of the use of a boundary-layer device to reduce buffeting noise, due to shock-induced separation on an aircraft cockpit, is described in Ref 41. The device used is an experimentally optimised arrangement of sub-boundary layer vortex generators (SBVG's, see Fig 27a) located over the cockpit. The benefit of using these small devices is that whilst effectively delaying the onset of shock separation, the device drag is much smaller than for conventional vortex generators and, in this particular application, their location within the subsonic region of the boundary layer avoids the generation of further shock waves which would act as additional noise sources. The effectiveness of the SBVG's in reducing buffeting is illustrated in Fig 27b, which compares accelerometer signals for both the original canopy and the final version employing the SBVG's.

8.3 Use of active control to reduce the response to buffet excitation

If an aerodynamic control surface is available which retains some effectiveness, even when the flow is separated, then active control technology may be used to increase the aerodynamic damping ratio, γ, in the modes excited and hence to reduce the response, $\ddot{z}$, given by equation (7). Generally, the control surface, eg a wing aileron or flap, will be outside the area of separated flow, but this may not be essential. Destuynder's experiment[42] suggests this method could be effective for civil aircraft, at least for light or moderate levels of buffeting.

9 PREDICTABLE BUFFET

Fair predictions of the buffet excitation can be made for two quite difference types of separated flows. These flows feature two-dimensional bubbles or two-dimensional periodic shock oscillations at transonic speeds.

9.1 Random pressure fluctuations due to bubbles

Two-dimensional bubbles occur widely in leading-edge separations on aerofoils, behind steps, downstream of sudden expansions in ducts, behind spoilers, upstream of steps or within a long shallow cavity (Fig 28). It has been found by experiment that the pressure fluctuations caused by these bubbles conform to a simple model[18]. The pressure fluctuations increase linearly from the separation point (S) and reach a maximum just upstream of the time-mean reattachment point (R), at a distance ℓ downstream of separation. The rms level of the maximum pressure fluctuations is in the range of $\bar{p}/q$ from 0.04 to 0.10. Here, with reference length $L = \ell$ the spectrum of the pressure fluctuations reaches a maximum of about $\sqrt{nF(n)} = 0.06$ at a frequency parameter $n = 0.6$ to 0.8. This simple model has been widely used and is recommended to estimate the severity of buffet excitation associated with two-dimensional bubbles.

It is thought that the above criterion may be of guidance for three-dimensional configurations where the type of separation is essentially the same. With due caution there are possible applications to buffet on wings and other aircraft components at low speeds.

Perhaps by the time of the specialist meeting it will be possible to predict the random pressure fluctuations due to a bubble, using CFD.

9.2 Periodic pressure fluctuations due to shock oscillations

At transonic speeds periodic shock oscillations at a single frequency have been observed over narrow Mach number ranges on bi-convex aerofoils at zero incidence[7,8] (Fig 29) and on supercritical aerofoils[43], above the design lift coefficient. Although the precise mechanism of this shock oscillation is still the subject of research, there is evidence that the oscillations depend primarily on three factors.

(1) Pressure perturbations propagating downstream from the shock to the trailing edge.

(2) Pressure perturbations propagating upstream from the trailing edge to the shock. (This factor is less important than (1) above.)

(3) The phasing of these disturbances relative to the motion of the shear layer downstream of the trailing edge.

Any modification of the boundary condition between the shock and the trailing edge, eg a transitional boundary layer or a porous surface or a buffet breather (section 8.2), will reduce the amplitude of the oscillations. Without such modifications, on bi-convex aerofoils the shock oscillations generate fluctuations of lift (±0.2 in C_L) and quarter-chord pitching moment (±0.1 in C_m) at a frequency parameter $fc/U = 0.16$, which is generally in the range of the wing first torsional frequency.

The shock oscillates at the same frequency, and this phenomenon can be predicted theoretically by two methods. The original method, due to Levy[44], uses the thin-layer Navier-Stokes solution. The more recent method, due to Le Balleur[43], uses an inviscid transonic small perturbation method in conjunction with a quasi-steady boundary-layer method which includes separation. The new method appears attractive to predict whether a given aerofoil design will have a periodic shock oscillation at transonic speeds, and over what range of Mach number and lift coefficient the instability would occur. The shock oscillations on bi-convex aerofoils are virtually independent of Reynolds number, and have the same frequency parameter for either fully laminar or fully turbulent boundary layers. They are therefore good test cases for establishing routine methods for predicting this special type of buffet.

10 DISCUSSION

This Paper has presented a comprehensive review of many aspects of the prediction of dynamic loading on aircraft, but two controversial questions remain to be discussed.

The first controversial question is the value of flight measurements, which are generally much less accurate than those in wind tunnels. Coe and Cunningham[23] have identified the main problems.

(1) Most flight measurements on combat aircraft are too short (typically 3 to 10 s) to give a significant number of cycles of buffeting. In contrast for the special tests of Ref 23 some light/moderate levels of buffeting were held for about 120 s, giving nearly 1000 cycles of buffeting in the wing first bending mode.

(2) Most flight manoeuvres on combat aircraft have transient aerodynamics and different levels of buffeting are achieved depending on, say the pitch rate. Such transient manoeuvres do not correspond to the 'steady' mean conditions of wind tunnel tests. This is well illustrated by the special flight comparisons presented in Fig 36 of Ref 23.

(3) For transport aircraft wing buffeting generally occurs because of an encounter with a transient gust (Fig 8) and "steady" conditions of buffeting may not be achieved before the aircraft leaves the gust, as discussed by Zbrozek and Jones[45].

In the view of the present author the main value of flight tests is to establish the 'ball-park' of the dynamic loading, eg is the buffet excitation 1, 10 or 100 kN/m^2? Often such information will suffice for the design of secondary structures, and provide a check on gross scale effects, which may become large at transonic speeds[46,47].

The second controversial question is the value of steady measurements when attempting to assess the dynamic loading. In the author's view dynamic loading can only be inferred with confidence from dynamic measurements. Experience suggests that direct inferences from steady measurements can be misleading[2,3,5]. However steady measurements, (such as pressure distributions) or flow visualisation (such as surface oil flow or even mini-tufts) can provide an indication of the areas of separated flow which contribute to the buffet excitation. This local information can be particularly valuable when attempts are made to alleviate the buffet excitation.

The author hopes that both of these questions will be addressed at the specialist meeting.

11 CONCLUDING REMARKS

This Paper illustrates the importance of a good knowledge of buffet in aircraft design and highlights the comparative lack of available detailed information. More detailed information should be provided by the specialist meeting. A set of definitions, and notation, is recommended for this meeting.

The importance of dynamic methods of testing is stressed, as is the optimum use of wind-tunnel models for this purpose, particularly with regard to the use of the buffet excitation parameter to assess the severity of buffeting and hence buffeting loads. The value of pressure distribution data and flow visualisation techniques in tunnel testing is endorsed as they bring a fuller understanding of the onset and consequent development of flow separations and buffet. Attention is drawn to the two cases of buffet for which prediction methods are currently available. Computation of the buffet excitation for these two cases, and for any other separated flows, represents a challenge for the CFD community.

Appendix A suggests a list of topics which should be discussed at the specialist meeting. Appendix B reproduces the first buffeting measurements in a cryogenic wind tunnel, reprinted (with Acknowledgements to the Royal Aeronautical Society) from section 3.8 of Ref 30.

APPENDIX A

SUGGESTED TOPICS TO BE DISCUSSED AT SPECIALIST MEETING

(1) All the problems shown in Fig 2, including single degree of freedom flutter (Fig 21).

(2) Measurements at low/moderate Reynolds numbers in conventional wind tunnels.

(3) Measurements over a range of Reynolds number in cryogenic wind tunnels (with particular reference to the evaluation of effects of scale, static aeroelastic distortion and frequency parameter).

(4) Measurements over a range of Reynolds number in flight.

(5) Comparisons between measurements of buffet excitation and predictions from CFD.

(6) Comparisons between measurements of buffeting response and predictions from CFD [both the buffet excitation and the aerodynamic damping would have to be predicted].

(7) Methods to alleviate both buffet and buffeting.

APPENDIX B

BUFFETING TESTS IN CRYOGENIC WIND TUNNELS

Kilgore et al have shown that the problems caused by static aeroelastic distortion in conventional wind tunnels should be much less severe in cryogenic wind tunnels (Ref 48). In cryogenic tunnels the kinetic pressure may be held constant for a constant total pressure while the Reynolds number is increased at constant Mach number by reducing the total temperature. This is an attractive concept for obtaining high Reynolds numbers at transonic speeds, and offers many advantages for buffeting tests on ordinary wind tunnel models (Ref 24). Boyden has made some buffeting measurements (Ref 25) in the NASA Langley 0.3 m transonic cryogenic tunnel on two solid aluminium alloy wings. The preliminary results from the wing-root strain gauges on the 65° delta wing are directly comparable with the measurements already discussed (Fig 7a&b) and are of great interest. In the subsequent figures, based on Boyden's data, the steady and unsteady signals from the wing-root strain gauges are divided by the kinetic pressure q, to form: a steady bending moment coefficient = $\overline{C}_B$, and an unsteady bending moment coefficient = C_B, exactly as in equation (9). Most of the unsteady bending moment response is at the fundamental bending frequency of 500 Hz at 300 K. The small increase in frequency at the lower total temperature is caused by the increase in Young's modulus. These comments by the author may stimulate further discussion of the technique.

Fig 30 shows how both bending moment coefficients vary with angle of incidence for a constant total pressure (P_t = 1.2 bar), two total temperatures (300 and 110 K) and a Mach number of 0.35. Now the kinetic pressure is the same at both total temperatures (Ref 48), so that the static aeroelastic distortion is identical for a given load. The steady bending moment coefficients, $\overline{C}_B$, are precisely the same at both total temperatures, confirming that scale effects are negligible on this highly swept slender wing over a wide range of Reynolds number. Before vortex breakdown the unsteady bending moment coefficients, C_B, are almost identical, despite the small change in frequency. This indicates that the excitation spectrum (due to the vortices and the tunnel unsteadiness) is relatively flat. In marked contrast, immediately after vortex breakdown the buffeting coefficients are quite different. The response is much higher at the higher frequency parameters obtained at the lower temperature. This increase in response with frequency parameter is consistent with the excitation measurements of Keating[5] on a similar planform (see spectrum of excitation in Fig 34). The large increase in response after vortex breakdown cannot be attributed to a decrease in the total damping coefficient, for this is estimated to increase from 1.3% to 1.6% of critical (due to the variation in aerodynamic damping) as the temperature is lowered from 300 K to 110 K.

Fig 31 shows buffeting measurements at 300 K for M = 0.35. For a given incidence the steady bending moment coefficients decrease as the kinetic pressure increases because of static aeroelastic distortion. The change cannot be attributed to the variation in Reynolds number because this is precisely the same as in Fig 30; comparison of Figs 30 and 31 thus strongly supports the claim that cryogenic tunnels can easily separate Reynolds number and aeroelastic effects (Ref 48). In contrast with Fig 30, the buffeting coefficients in Fig 31 only vary a little after vortex breakdown because the frequency parameter is constant. The buffeting coefficients vary a little with kinetic pressure both at low incidences and after vortex breakdown. This small variation is consistent with the estimated small variation in the damping coefficient from 1.4% to 1.6% of critical (due to the variation in aerodynamic damping.)

Fig 32 shows the effect of an increase in Mach number from 0.21 to 0.35. These special measurements are made at a constant frequency parameter (obtained by using a constant velocity of 73 m/s) and at constant kinetic pressure (obtained by using a constant density). When these two parameters are constant, the aerodynamic damping, proportional to the product of density × velocity, is constant. The steady bending moment coefficients increase rapidly with Mach number; the increase in bending moment coefficient looks appreciably larger than the expected increase in lift-curve slope. In contrast, the buffeting coefficients are virtually identical both before and after vortex breakdown, despite the difference in Mach number and the corresponding differences in the steady bending moment coefficients. The excellent agreement between both sets of buffeting coefficients after vortex breakdown is a direct consequence of maintaining a constant frequency parameter, and, to a lesser degree, of maintaining constant total damping (aerodynamic + structural), estimated to be 1.6% of critical. The importance of maintaining the correct frequency parameter in a buffeting test in a cryogenic wind tunnel was stressed previously (Ref 24).

The difficulty of achieving low structural damping and significant aerodynamic damping during buffeting tests on ordinary wind tunnel models has long been appreciated (Ref 10). Most of the structural damping on an ordinary wind tunnel model is caused by friction between the wing and the root fixing. As long as both the wing-root and the attachment are at the same temperature and of the same material, the friction should be unchanged in a cryogenic wind tunnel test. Then there would be no a priori reason for a change in structural damping coefficient with total temperature. The wind-on structural damping coefficient inferred from the present buffeting measurements (Fig 31) is about 1% critical, which is typical of an ordinary wind tunnel model. The wind-off measurement is only about 0.3% critical at ambient conditions. The aerodynamic damping coefficient was estimated theoretically (Ref 11).

The aerodynamic damping obtained in a buffeting test at constant Mach number and total pressure in a cryogenic wind tunnel is $1/\sqrt{T_t}$ (Ref 24). Hence the proportion of aerodynamic to structural damping will increase at cryogenic temperatures. This will improve the scaling of the aerodynamic damping ratio from model to full scale (Ref 24).

Some measurements of the total damping coefficients derived from the power spectra of the wing-root strain signals have been added; these measurements are in fair agreement with the estimates (Fig 33).

Fig 34 shows the spectrum of the excitation measured at vortex breakdown. Although the geometry of the BAC 221 was appreciably different from a 65° delta wing, it is known that the flows on both wings are broadly comparable. The large increase in excitation from a frequency parameter, fc_o/V , from 0.8 to 1.4 is consistent with the increase in response shown in Fig 30. The spectrum of the excitation measured on unswept rectangular wings is generally flatter than that shown in Fig 34, and hence Boyden's buffeting measurements on the other wing are not sensitive to the variation in frequency parameter.

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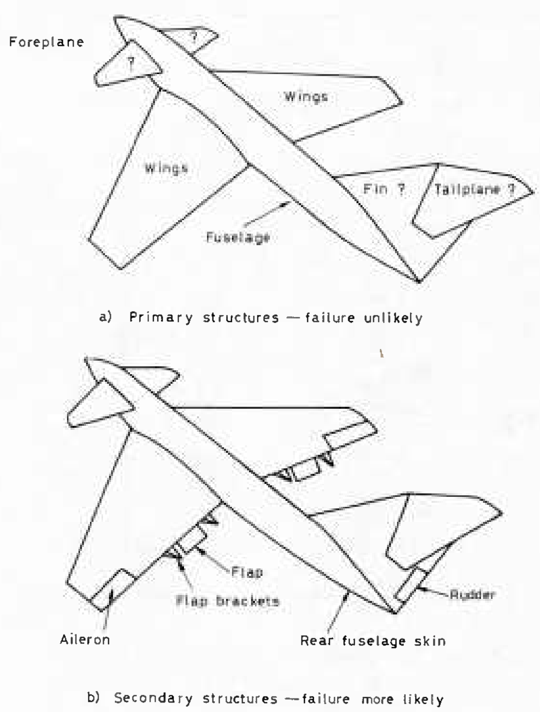


Fig 1 Effects of dynamic loads due to separated flows

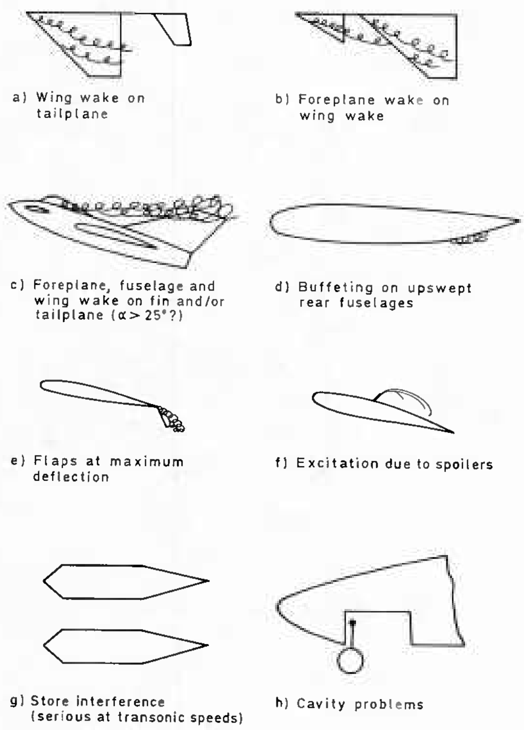
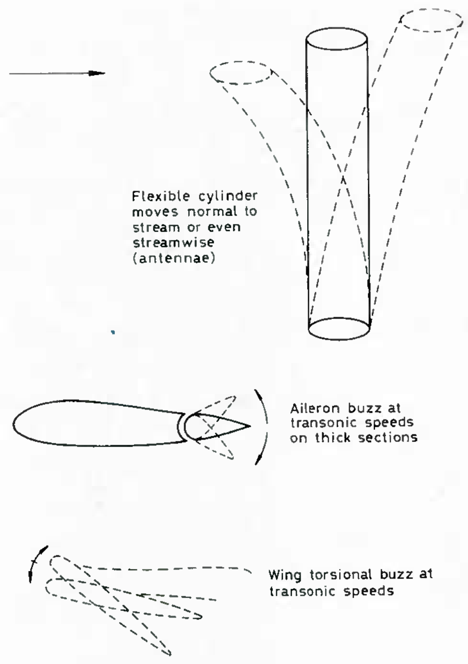


Fig 2 Typical dynamic loads problems to be addressed at specialist meeting



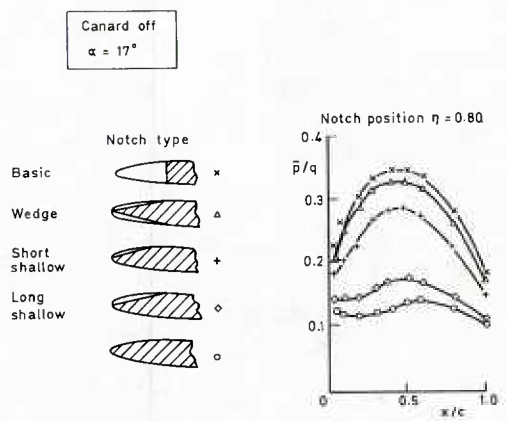
i) Types of amplitude – limited single – degree of freedom flutter or buzz

Fig 2(concld) Typical dynamic loads problems to be addressed at specialist meeting

Flow		rms level $\bar{p}/q$	Spectrum level $\sqrt{nF(n)} = \Delta p/q\sqrt{\varepsilon}$
Attached : Zero pressure gradient		0.005 to 0.006	0.002 to 0.003
Attached : Adverse pressure gradient		0.01 to 0.02	?
Reattachment point of bubble	R	About 0.10 (Ref 18)	About 0.06 (Ref 18)
Separation combined with aerodynamic resonance (single frequency)		0.50 (Ref 8)	Shock oscillation -biconvex aerofoils
	R_1 R_2	0.55 (Ref 19)	Bistable-flow separation on swept wings
		(Ref 20)	Karman shedding frequency=acoustic resonance frequency of duct

a) General classification

Fig 5 Levels of buffet (excitation) rms and spectra



b) Influence of notch type on total broad-band rms pressure fluctuations

Fig 5(contd) Levels of buffet (excitation) rms and spectra

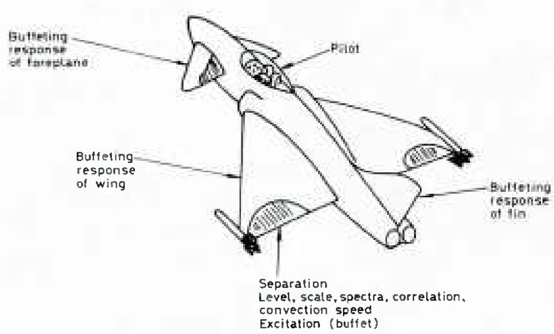


Fig 3 Buffet and buffeting

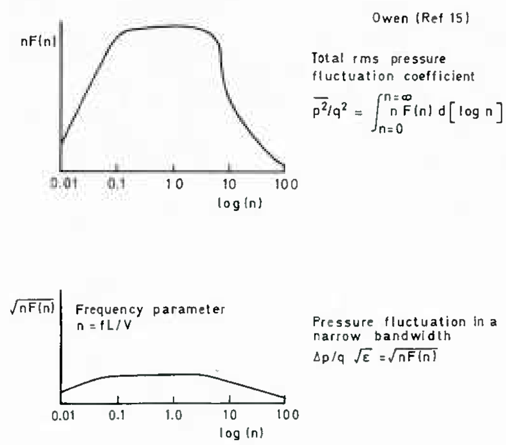
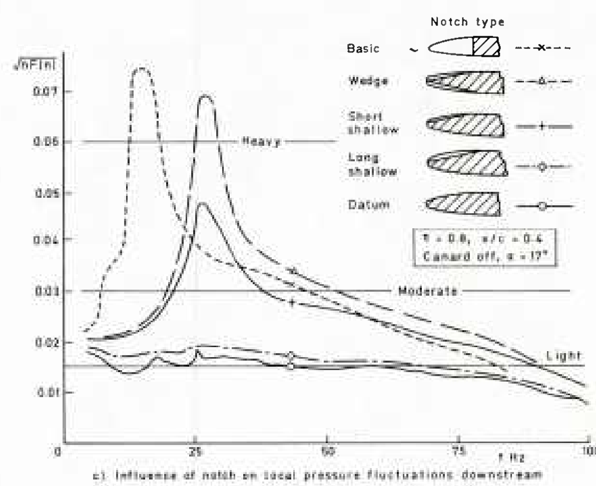
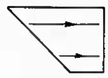
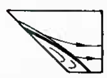
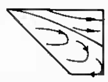
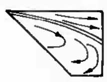


Fig 4 Dimensionless representation of buffet excitation spectra



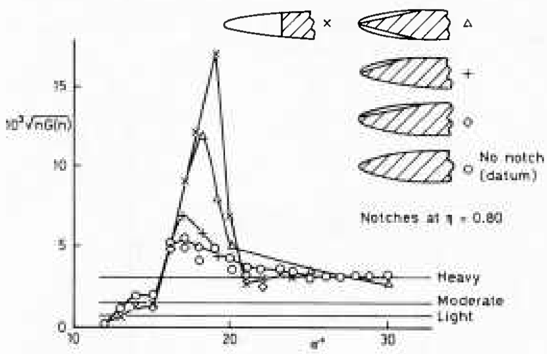
c) Influence of notch on local pressure fluctuations downstream

Fig 5(concld) Levels of buffet (excitation) rms and spectra

Types of flow / Buffeting	Spectrum level $\sqrt{nG(n)} = \frac{2}{\sqrt{\pi}}\left[\frac{m\ddot{y}}{q\,s}\right]\xi^{1/2}$ Buffet excitation parameter	
Attached / Nil		0.0002 to 0.0004
Just separated / Light		0.00075
Separated / Moderate		0.00150
Well separated / Heavy		0.00300
Well separated + resonance / Very heavy		0.009 or higher ?

a) General classification

Fig 6 Levels of buffeting (response) spectra



b) Wing buffet excitation parameter with notches

Fig 6(concld) Levels of buffeting (response) spectra

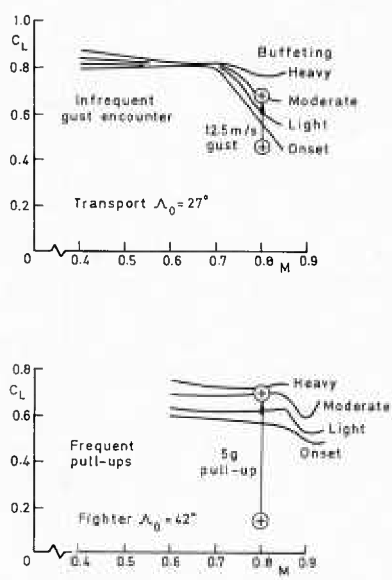


Fig 8 Buffeting criteria for transport and fighter aircraft

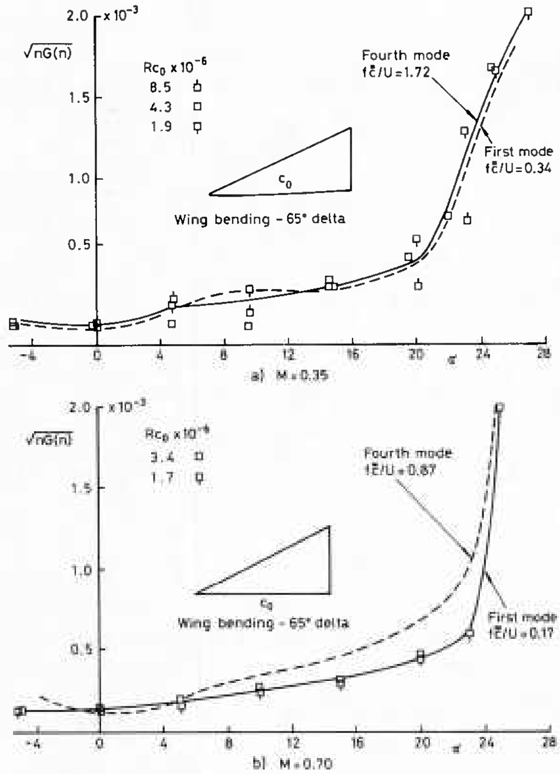
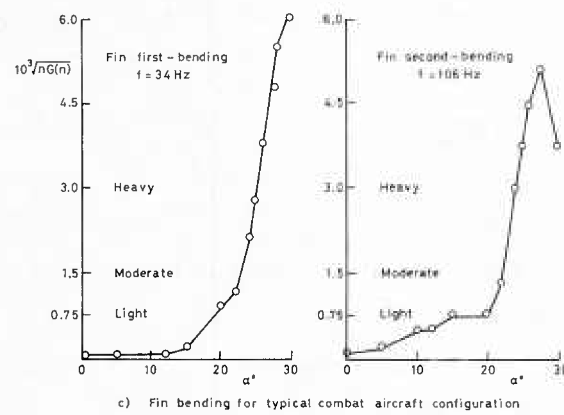


Fig 7 Insensitivity of buffet excitation parameter to changes in mode shape and frequency parameter



c) Fin bending for typical combat aircraft configuration

Fig 7(concld) Insensitivity of buffet excitation parameter to changes in mode shape and frequency parameter

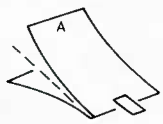
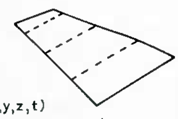
Method	Advantages	Disadvantages
a) Measurement of buffeting (response) with tip accelerometers or root strain gauge 	Simplicity reliability	Only appropriate to primary structural modes. Works well in bending, less well for torsion
b) Measurement of buffet (excitation) with pressure transducers  p (x,y,z,t) Both surfaces!	Predictions of buffet excitation for any mode. May help to identify source of excitation	Assumptions must be made about aerodynamic damping. Large number of transducers. Large computer

Fig 9 Methods of predicting the buffet excitation parameter

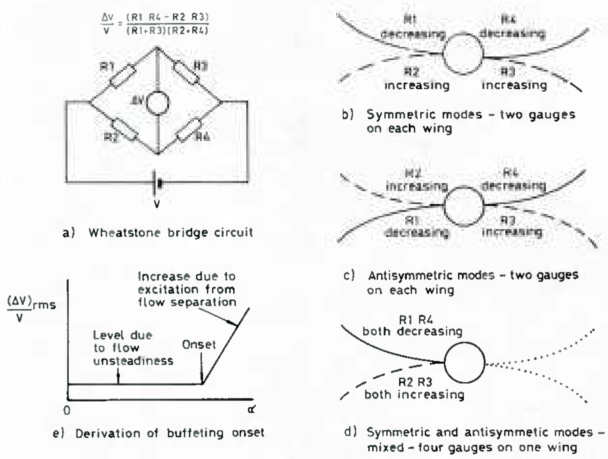


Fig 10 Use of root-strain gauges for buffeting tests

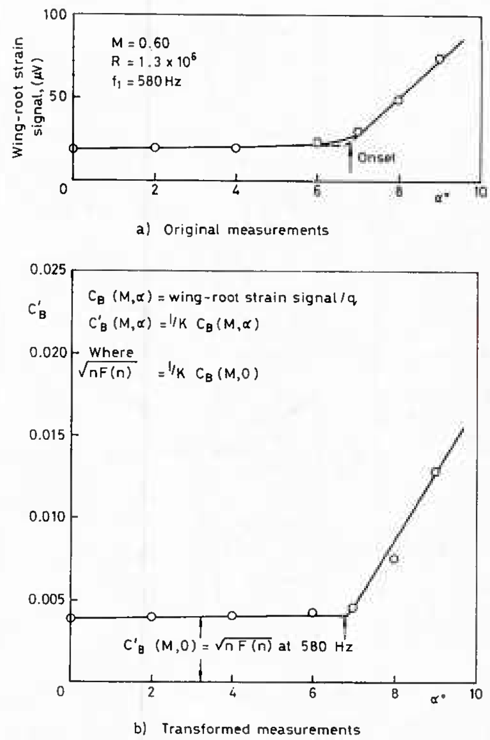


Fig 11 Definition of buffeting coefficients (data from reference 29)

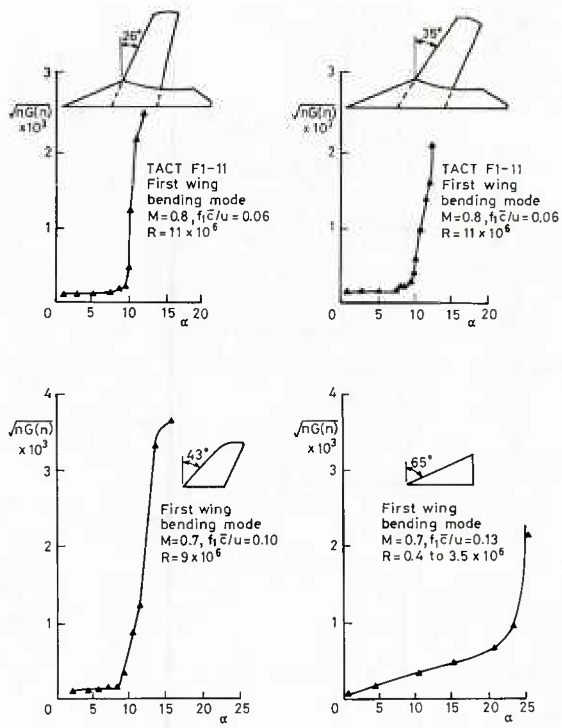


Fig 12 Wind-tunnel results of buffeting tests represented in terms of $\sqrt{nG(n)}$ and α

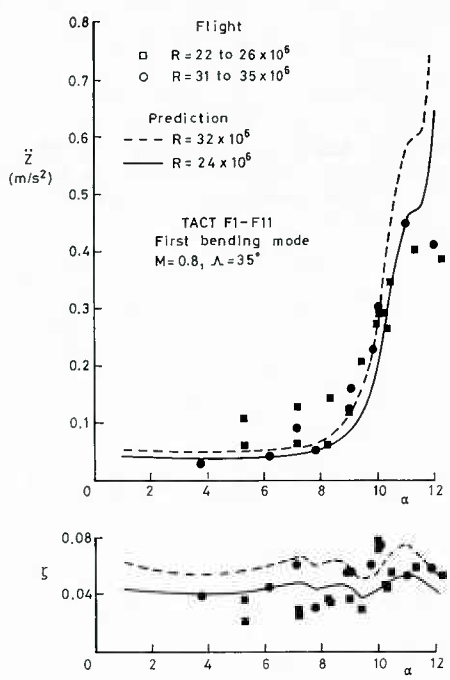


Fig 13 Predicted and measured rms wing-tip acceleration and damping ratio at full scale

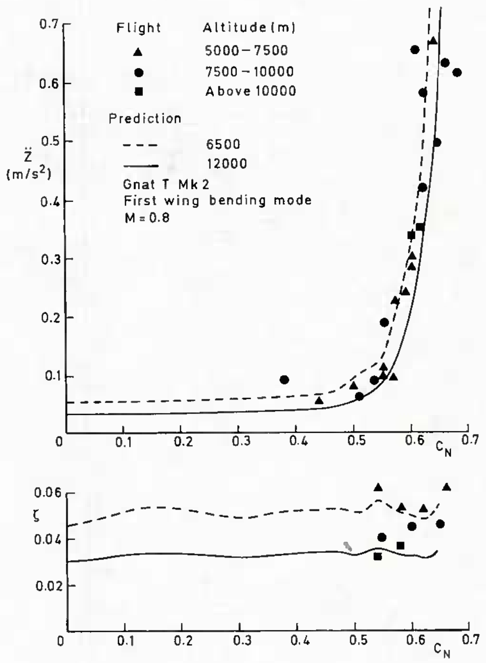


Fig 14 Predicted and measured rms wing-tip acceleration and damping ratio at full scale

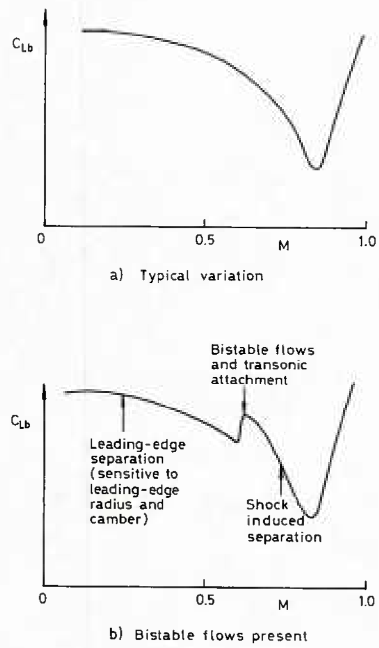
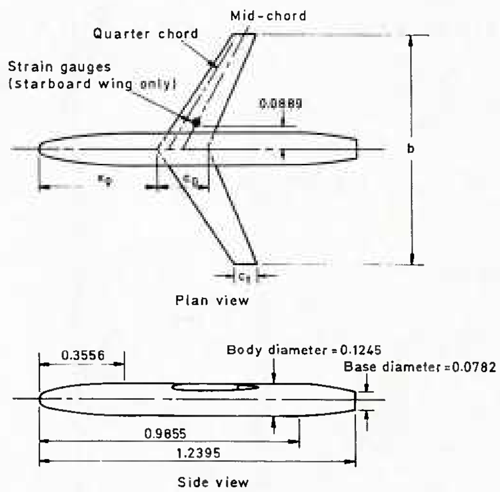


Fig 16 Variations of C_{Lb} with Mach number



Model characteristics

Wing	NACA aerofoil section	$\Lambda_{\frac{1}{4}}$ (degree)	c_t (m)	c_0 (m)	b (m)	S (m^2)	A	x_0 (m)
1	63A008	25	0.0871	0.218	0.914	0.139	6	0.4895
2	63A008	35	0.0871	0.218	0.914	0.139	6	0.4793
3	63A008	45	0.0871	0.218	0.914	0.139	6	0.4658
4	63A006	35	0.0871	0.218	0.914	0.139	6	0.4793
5	63A010	35	0.0871	0.218	0.914	0.139	6	0.4793
6	64A008	35	0.0871	0.218	0.914	0.139	6	0.4793
7	65A008	35	0.0871	0.218	0.914	0.139	6	0.4793
8	63A208	35	0.0871	0.218	0.914	0.139	6	0.4793
9	63A408	35	0.0871	0.218	0.914	0.139	6	0.4793
10	63A008	35	0.1070	0.267	0.747	0.139	4	0.4775
11	63A008	35	0.0955	0.239	0.835	0.139	5	0.4785

Fig 15 Typical buffet model as used in reference 2. All dimensions in m

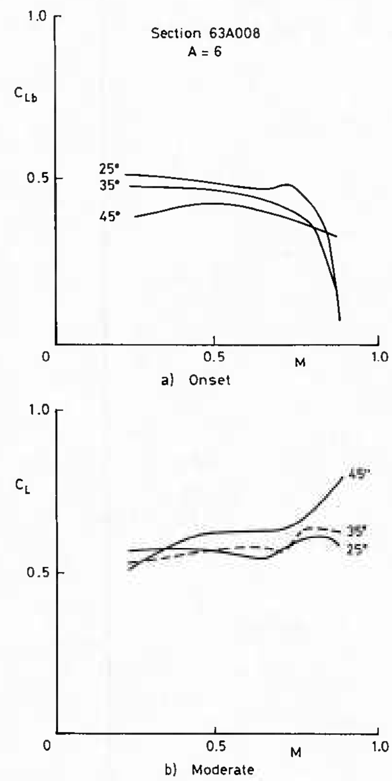


Fig 17 Effect of sweep ($\Lambda_{\frac{1}{4}}$) on buffeting

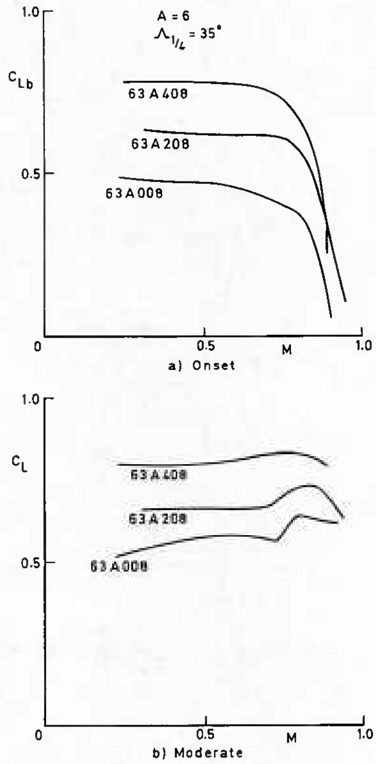


Fig 18 Effect of camber on buffeting

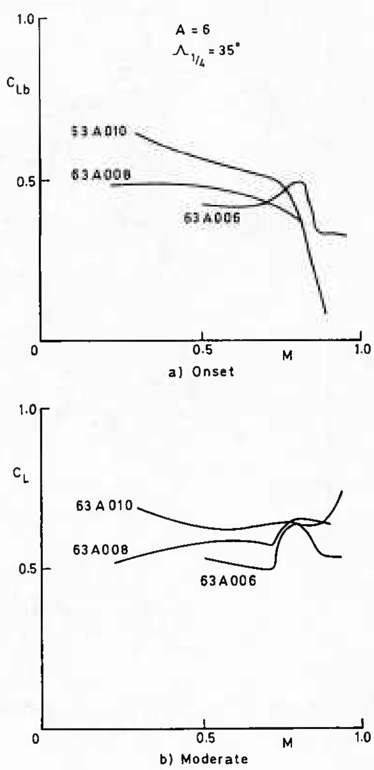


Fig 19 Effect of thickness/chord ratio on buffeting

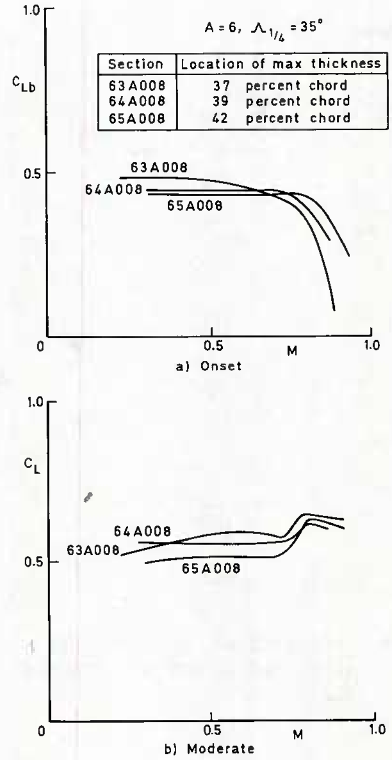


Fig 20 Effect of position of maximum thickness on buffeting

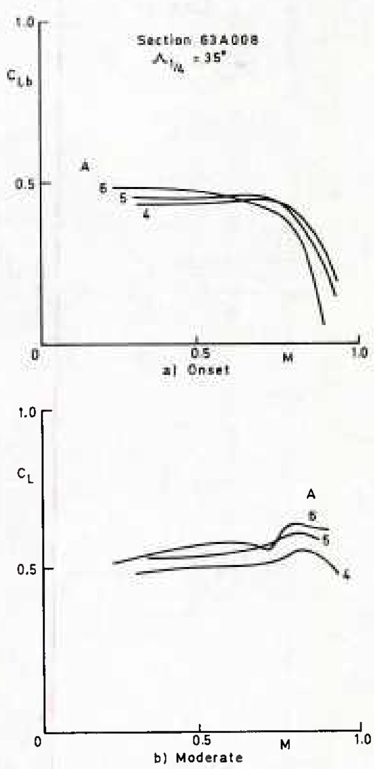
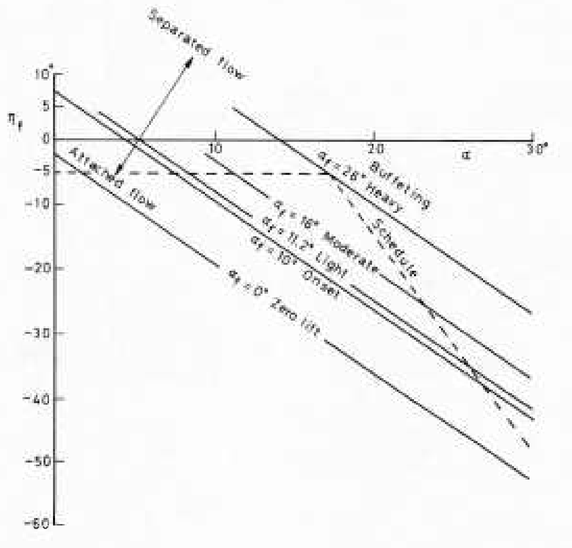
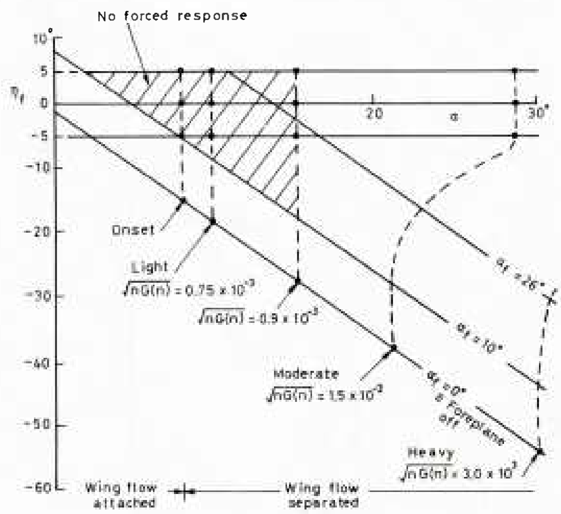


Fig 21 Effect of aspect ratio on buffeting



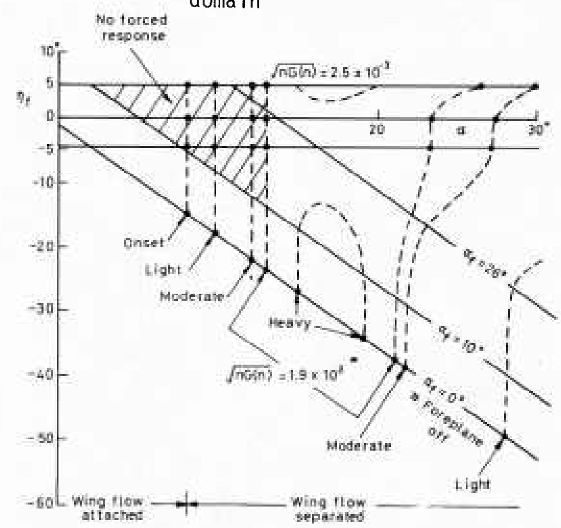
a) Foreplane flow and buffeting

Fig 22 Representation of foreplane/wing buffeting in α, η_f domain



b) Wing flow and buffeting in first-bending mode

Fig 22(contd) Representation of foreplane/wing buffeting in α, η_f domain



c) Wing flow and buffeting in overtone bending mode

Fig 22(concld) Representation of foreplane/wing buffeting in α, η_f domain

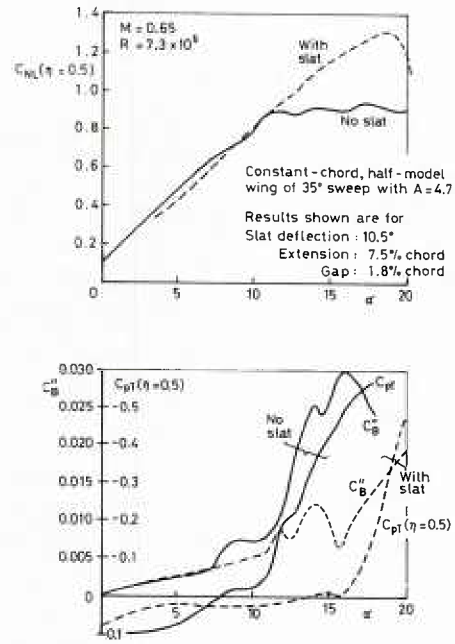
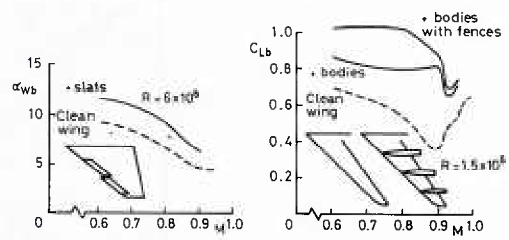


Fig 23 Example of the effect of leading-edge slats on buffeting (reference 35)



a) Leading-edge slats

b) Area-rule bodies and boundary-layer fences

Fig 24 Alleviation of buffeting by wing modifications

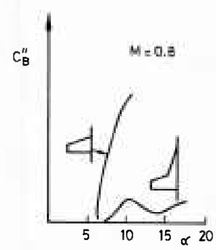


Fig 25 Effect of strake on wing buffeting (reference 38)

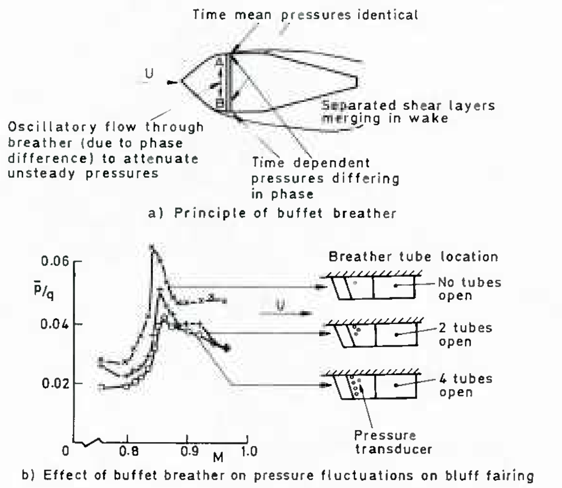


Fig 26 Use of buffet breathers to reduce buffet (reference 39)

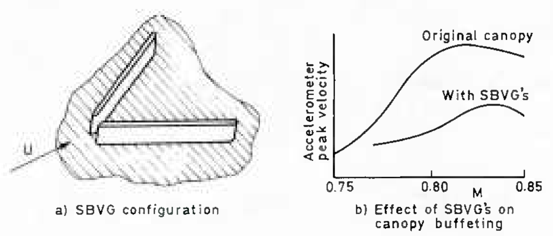


Fig 27 Use of sub-boundary layer vortex generators to reduce buffeting (reference 41)

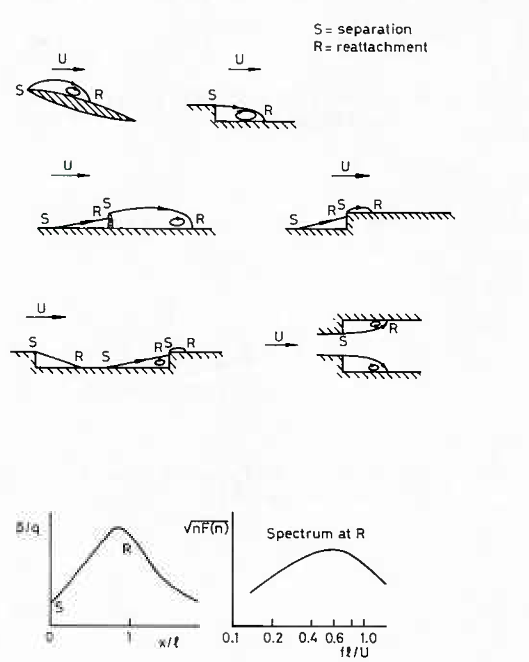


Fig 28 Types of bubble flow (after references 5 and 18)

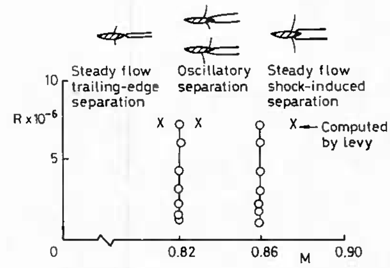


Fig 29 Flow domains for a 14% thick biconvex aerofoil $\alpha = 0^0$ (fixed transition)

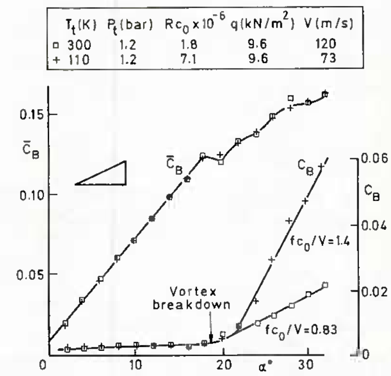


Fig 30 Negligible influence of Reynolds number $M = 0.35$

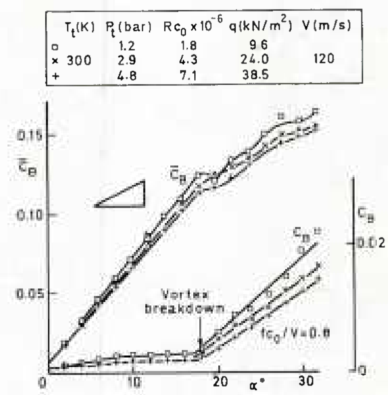


Fig 31 Influence of static aeroelastic distortion $M = 0.35$

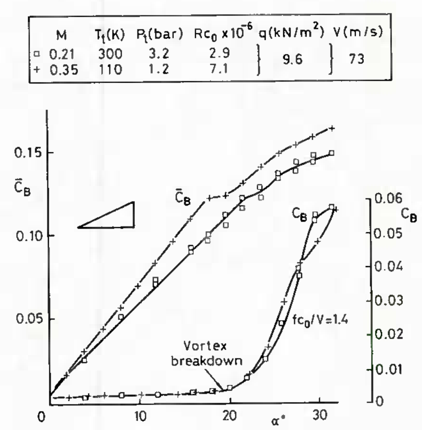


Fig 32 Influence of Mach number

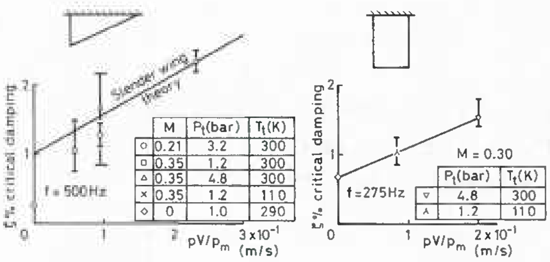


Fig 33 Preliminary damping measurements for buffeting tests in cryogenic wind tunnel

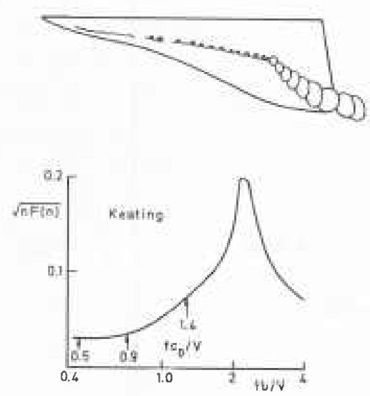


Fig 34 Spectrum at vortex breakdown

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